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## Optimization of a self-peeling vat for precision vat photopolymerization setups

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### Abstract

This paper presents the optimization of a state-of-the-art self-peeling vat for vat photopolymerization (VP) processes. One of the research goals of the Additive Manufacturing (AM) group from the Technical University of Denmark is to achieve the highest resolution, maximum precision and process optimization for the AM machines and the fabricated components. To achieve this goal, it is essential to have control over every single stage of the manufacturing process. One concern mayor concern in VP is the vat performance, which has to withstand with adhesion forces and wear. The previous setup designed by this research group already outperformed industrial vats by 814% [1], by lowering the normal forces induced by the adhesion between the vat and the part with the aid of a flexible membrane system. Although an improvement on the release-capability was achieved, failure was found in several materials with higher material bonding, which ultimately deformed the surface of the parts. In this work, optimization is achieved by increasing the surface area of the vat, diminishing the stress on the membrane. The building area is moved from the center which creates different peeling angles on each side of the part. The angle asymmetry combines easy peeling with low forces, together with an induced passive tilting mechanism that leads to higher quality of the manufactured samples when microfeatures are present.

Vat photopolymerization, additive manufacturing, surface adhesion, FEP membrane.

### 1. Introduction

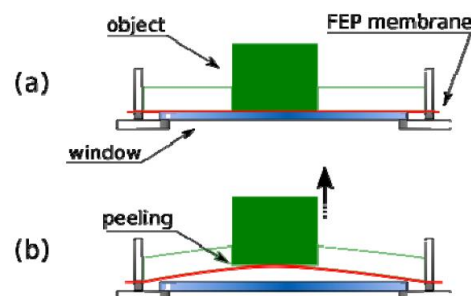
Vat-based photopolymerization (VP) is an Additive Manufacturing (AM) technology which allows the fabrication of highly complex and customizable components with excellent geometrical tolerances compared to other AM strategies [1]. In this process, a liquid resin is selectively exposed to UV light and irreversibly crosslinked. The hardened area corresponds to one cross-section of the selected geometry that was previously sliced. Subsequently, the machine repositions the building plate to allow the curing of the next layer, this cycle is repeated until the object is completed. VP has moved on from being a fast prototyping tool to gain an exponential popularity among diverse healthcare industries— from the fabrication of end-use hearing aids where 90% of the inner-ear shells are manufactured with the so-called Digital Light Processing (DLP) which allows relatively large scale manufacture of parts with reduced build speeds, to research areas such as microfluidics and scaffolds, just to name a few [2], [3].

The growing interest in VP also calls for further development in its hardware to achieve robustness, repeatability and even higher quality parts to eventually bring this technology toward a high precision manufacturing level.

#### 1.1. Background and motivation

The layer formation in DLP vat photopolymerization is typically formed in the bottom of the vat, then carried upward. This setup allows higher layer thickness control and better crosslinking kinetics since it is not in direct contact with air, which has proven to inhibit the photopolymerization. However,

one of the biggest concerns of the bottom-up configuration is the separation force between the crosslinked layer and the vat surface. Traditional vats are coated with a polydimethylsiloxane (PDMS) layer, which reduces the adhesive forces but can still lead to failure, especially when the surface area in contact with the vat exceeds the surface area in contact with the building plate. To overcome these adhesive forces, a flexible membrane vat with a flexible Fluorinated Ethylene Propylene (FEP) was developed and verified at the Technical University of Denmark (Figure 1), achieving an outstanding performance gain of 814 % relative to an industrial vat from EnvisionTEC GmbH [4].



**Figure 1.** The first iteration of the flexible vat with self-peeling principle developed at DTU. a) Resting position and b) lifting sequence [4].

This state-of-the-art open additive machine-tool not only outperformed the capabilities of industrial configurations, but also showed no failure during the object fabrication and allowed the research group to fabricate microstructures

comparable to those manufactured with other micro-manufacturing strategies such as soft lithography [5]. However, it was observed that the FEP membrane suffered creep during the process which affected the repeatability of microfeatures, as well as the membrane endurance. The aim of this study is to further improve this self-peeling mechanism by reducing the peeling forces and increasing the membrane durability, and to achieve micro-sized feature replication and repeatability in the manufactured parts. In order to address this challenge, two vat shapes were designed and compared to assess their performance.

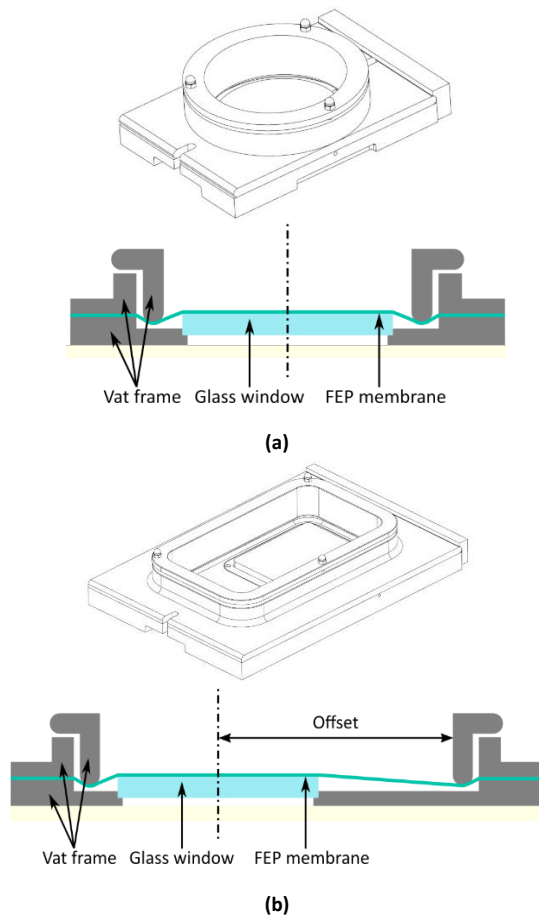
## 2. Materials and methods

### 2.1. Hardware

The updated flexible vat was implemented in a novel AM DLP machine, designed, built and validated at the Technical University of Denmark. The DLP is configured with a LRS-WQ - HY Light Engine, integrated with a XY high-resolution DLP9000 WQXGA (2560x1600p, with 7.54  $\mu\text{m}$  pixel pitch) Digital Micromirror Device (DMD) micro display. The Z axis has a linear stage with a vertical resolution of 0.625  $\mu\text{m}$ . The film used for the experiments was a clear fluoroplastic DuPont™Teflon®FEP sheet.

### 2.2. Vat designs

Two design configurations were studied and compared. Both designs include an updated feature compared to the previous iteration where in order to provide an easy membrane installation and ensure uniform tightness, a “drum” inspired fastener mechanism was design and implemented.

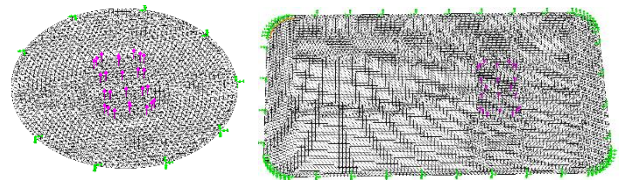


**Figure 2.** (a) CAD model of the round vat and cross section showing the drum fastening mechanism (b) CAD model of the rectangular-offset vat and cross section showing the drum fastening mechanism with an offset glass window.

Figure 2 shows the two suggested concepts. The purpose of the simplest design, the round shaped vat, is to obtain equal initial peeling angles around the sample. The second design was designed rectangular and offset from the center to offer different peeling angles around the sample to act as a non-mechanical tilting effect (in addition to the self-peeling effect produced by the FEP film) seen in other commercial DLP applications which have shown superior performance over the non-tilted[4]. Both designs also differ in the ratio between membrane surface area and building envelope area with 8.44 and 23.42 for the round and the rectangular vats, respectively.

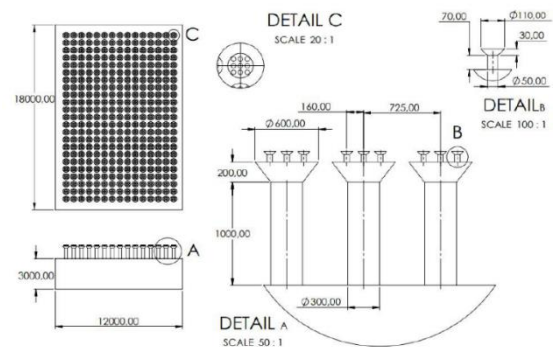
### 2.3. FEA simulation and performance validation

In order to compare the performance of the vats, both designs and the effect of the pulling forces on the membrane were simulated using the Finite Element Analysis module in Solidworks. The models of each vat were represented by the section of the film under stress with their respective shapes (round and rectangular). Figure 3 shows the meshed models of each of the film geometries. The green arrows represent the drum frame that fixes the membrane, and the pink arrows simulate the pull-out forces when the part is detached, the area covered by the arrows is the maximum building area of the DLP. Two prescribed pull-in forces of 2.5N and 0.5N were applied to the membrane, based on a previous study [6] as the maximum and minimum forces the membrane will withstand during the manufacturing process. One of the main drawbacks of using a membrane is that it is a consumable that wears out and needs to be changed regularly to keep its optical properties and prevent it from breaking and pouring the liquid resin over the glass window of the vat. Accordingly, finding the design that delivers less stress on the membrane will yield an optimized process.

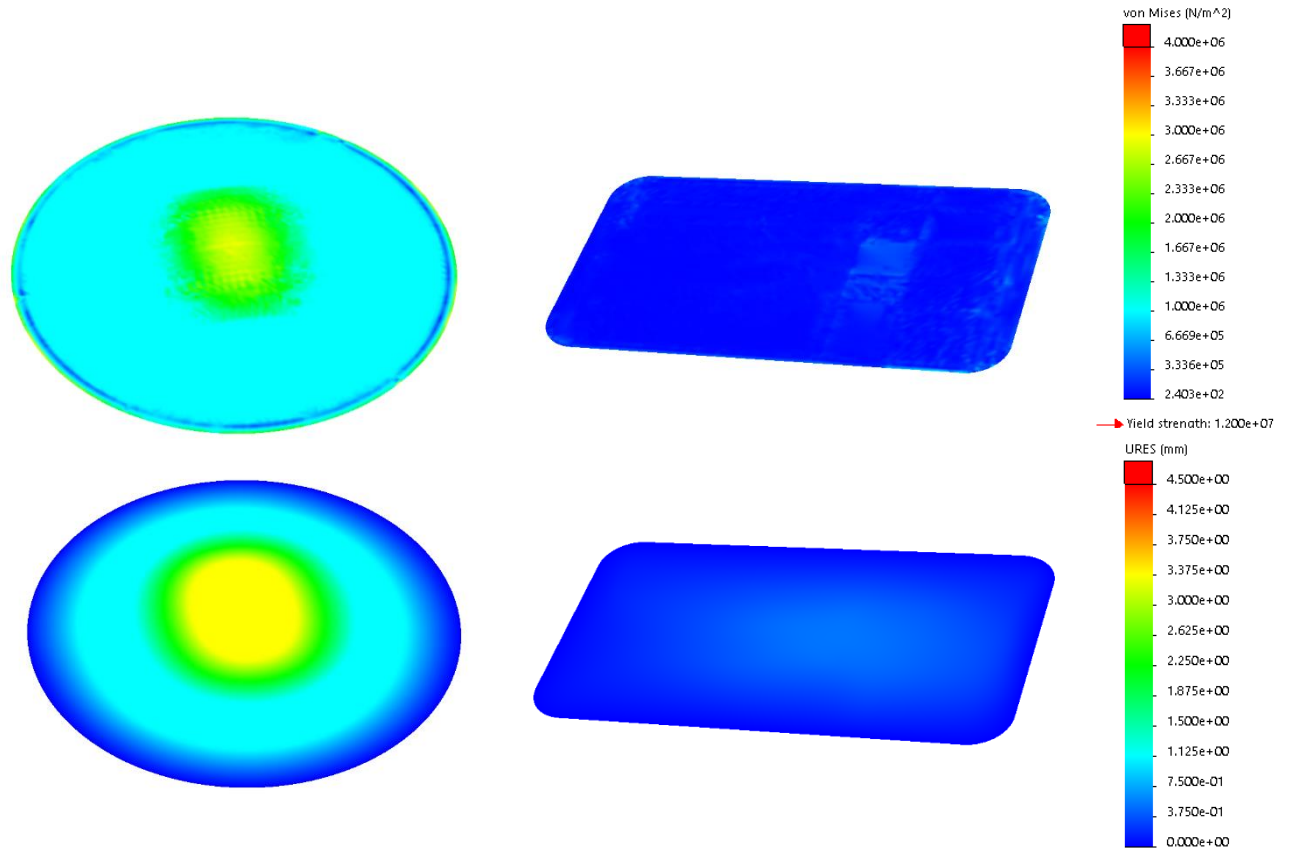


**Figure 3.** Meshed models of the round and rectangular vats.

Both vats were manufactured in the Technical University of Denmark workshop and compared to assess which one performs better when a sample with microstructures is fabricated. The samples manufactured (Figure 4) consist of a functional surface with small mushroom-shaped pillars mimicking features of a gecko toe whose performance was previously studied [5].



**Figure 4.** Schematics of the manufactured samples.



**Figure 5.** FEA simulation results for the round and rectangular vat, the upper diagrams represent the Von Misses stress that the membranes undergo when the 2.5 N pull-out force is applied, the lower diagrams show the displacements.

### 3. Results and discussion

#### 3.1. FEA simulations

The finite element analysis results shown in Table 1 show the maximum stress that the round and rectangular vats withstand under 0.5 N and 2.5 N pulling forces, as well as the displacements of the membrane under those circumstances. As expected, the maximum values are found in the area where the pull-out forces are applied. Worth noting, is that none of the designs reach the yield strength of the FEP membrane (12MPa). There is a significant difference between both designs where the round design will suffer higher stresses with a maximum of 2.88 MPa when the 2.5 N force is applied (worst case scenario), meaning that the membrane will wear and tear faster than the rectangular membrane which undergoes pull-out forces six times smaller than its competitor (0.43 N). Accordingly, the round vat also experiences higher displacements (3.99 mm at 2.5 N and 1.07 mm at 0.5 N). In the rectangular vat these displacements are almost neglectable as seen in Figure 5.

**Table 1.** FEA comparison of maximum stress and maximum displacement between the round and rectangular vat.

	Round		Rectangular	
	0.5 N	2.5 N	0.5 N	2.5 N
<b>Max. stress [MPa]</b>	1.07	2.88	0.34	0.43
<b>Max. displ. [mm]</b>	2.33	3.99	0.1	0.5

Although the rectangular vat promises improved behaviour in terms of membrane endurance, further studies will be necessary to assess its behaviour under a cyclic load which better represents the DLP behaviour during the manufacturing process. Moreover, the small displacements in the rectangular vat most likely indicate that the peeling angle might also be neglectable, meaning that the self-peeling mechanism will be

less effective, since the higher the peeling angles are, the peeling will be more effective therefore lower detachment forces will be achieved. Since this FEA study considers a pre-defined pull-out force, this phenomenon is not reflected in the results. Nevertheless, this FEA analysis may forecast which design will benefit the membrane endurance.

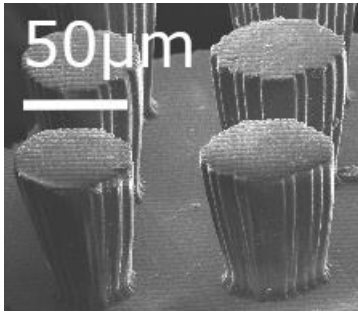
In order to validate this conclusion, both vats were manufactured, and the membrane wear was monitored by keeping track of how many parts were achievable before the membrane failure occurs. Failure was considered when the microfeatures of the parts were not reproduced or when it was visibly deformed. In total, five membranes were used for each design. The rectangular vat showed higher membrane endurance with an average of 30 parts manufactured before failure, whereas the round vat demonstrated lower performance with an average of 15 samples made before failure. These results are in agreement with the FEA conclusion that the rectangular vat would endure longer than the rounded.

#### 3.2. Manufacturing performance

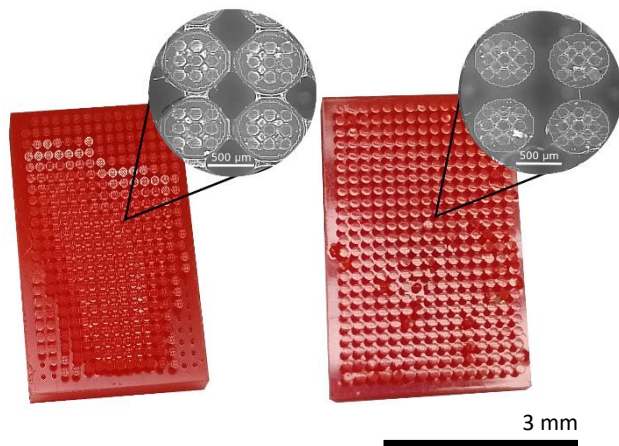
One of the limitations of the FEA simulations is the lack of information about how well it would perform when microfeatures are manufactured. A preliminary test subject in the shape of a truncated cone was manufactured in both vats to ensure that their capabilities match the peeling performance of the old design, in both cases the test was a success.

When the sample with microstructures was manufactured, the microstructures were reproduced in both setups with the smallest features visible under the scanning electron microscope, SEM, (Figure 6). However, the quality of the overall samples visibly differed from one vat to the other, where the rectangular vat again demonstrated higher performance.





**Figure 6.** SEM image of a small area from one of the pillars, the smallest pillars seen in the picture are 100  $\mu\text{m}$  tall with 50  $\mu\text{m}$  diameter on the base and 110  $\mu\text{m}$  on the top.



**Figure 7.** Microstructured sample manufactured with the round vat (left) with a visible sink area on the surface, and rectangular vat (right) showing a uniform array of pillars (the bent pillars were deformed during the drying process after manufacturing).

The excessive deformation and possible higher adhesive forces on the membrane led to a sink mark, which covered a significant area on the surface of most of the samples manufactured with the rounded vat (Figure 7, left). The shape of the sink mark followed the same pattern in all samples that showed this defect. The pillars from the rectangular vat samples had almost identical heights and were separated from their neighbouring pillars across the entire surface. The uneven detachment angle due to the offset and the higher ratio between the vat surface area and printing area in the rectangular vat are most likely the reasons for the higher quality of the samples. These differences between samples confirm that the rectangular vat is the best design option for both, membrane endurance and microfeatures replication.

#### 4. Conclusion

This study aimed to improve the self-peeling vat capabilities in terms of membrane endurance and microfeature replication. Two designs were proposed: a round and rectangular vat. They were simulated using Solidworks FEA to assess the stresses seen by the membrane and to predict which design would provide a longer membrane lifetime, therefore reducing consumable waste. The concepts were also manufactured to investigate their ability to reproduce and replicate geometries with microfeatures.

The results show that the rectangular vat has superior capability in terms of membrane endurance with an average of 30 parts successfully manufactured before failure and reproduced higher quality samples by replicating the

microstructured fine pillars over sample surfaces, whereas the round vat had a lower membrane lifespan with an average of 15 samples fabricated before failure and lower microfeature quality.

This research opens the door to produce highly complex FEA models to study the peeling effect seen in VP technologies and predict the behaviour of the machine prior to its fabrication. It also raises awareness of the impact of the peeling mechanism when high-resolution geometries with microstructures are present. Achieving these features is becoming a growing interest in areas developing bio-inspired materials, smart surfaces or microrobots in drug delivery, where AM is gaining popularity due to its immediacy and relatively low cost compared to other nano- or micromanufacturing processes that often require time, expertise and a bigger investment in laboratory equipment [7], [8]. Here, the suggested vat design alleviates a source of error found at this micro scale manufacturing, where the only resolution limitation should be found at the light source of the device in use.

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